

Activation analysis of fusion divertors based on K-doped W and low-activation materials (V, ARAA)

Seonghee Hong and Sungjin Kwon
Korea Institute of Fusion Energy, Daejeon, Rep. of Korea, 34133
*Corresponding author: shhong@kfe.re.kr

***Keywords** : divertor, activity, W/Cu/CuCrZr divertor, W/V/ARAA divertor, K-doped W divertor

1. Introduction

Currently, the ITER grade divertor primarily utilizes a tungsten (W) armor, a copper interlayer, and a CuCrZr heat sink (HS). Although Cu-based alloys offer excellent thermal conductivity, they are susceptible to activation by neutron irradiation, limiting their application in DEMO grade fusion reactors, which require significantly increased fusion output and operating life. To overcome this issue, vanadium (V) interlayers and reduced-activation ferritic/martensitic steel (RAFM) HS are being actively considered as replacements for existing Cu-based components.

Furthermore, the use of K-doped W, with small amounts of potassium (K) added, is emerging to increase the recrystallization temperature of the tungsten armor, thereby enhancing thermal performance and durability. Therefore, in this paper, in order to verify the feasibility of divertor materials in terms of activation, a simplified layered model was used to evaluate the activation analysis of W/Cu/CuCrZr, W/V/Advanced Reduced Activation Alloy (ARAA), K-doped W/Cu/CuCrZr, and K-doped W/V/ARAA combinations.

2. Calculation Model

The analysis model used for the activation evaluation is shown in Fig. 1. To simplify the model, only the W monoblock, cooling channel, and RAFM steel cassette body were included; their respective thicknesses are summarized in Table 1. Reflective boundary conditions were applied along the X and Y axes. The chemical compositions of the materials were defined as follows: W and Cu ITER grade [1], CuCrZr UNS CW106C [2], and V V4CrTi0.05Si [3]. ARAA, a Korean-type low-radiation steel, was used as the RAFM. The neutron wall loading was set to a maximum value of 1.7058 MW/m² based on the double-null K-DEMO divertor. The neutron analysis was performed with MCNP6 using the FENDL 3.1 cross section library, and the activation analysis was performed with FISPACT-II using TENDL2017 cross section library [4-7].

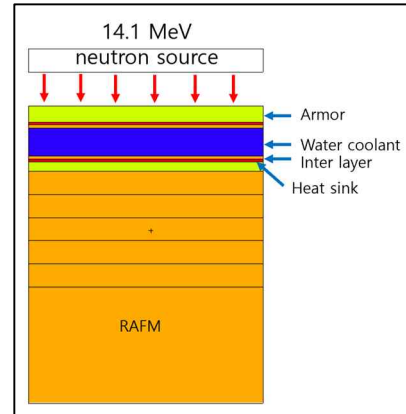


Fig. 1. MCNP model for divertor activity analysis

Table 1. Material thickness of the MCNP model for divertor activation evaluation

Material	Thickness (cm)
W	2.8
Heat Sink (HS)	1
Interlayer	1
Water coolant	$r = 0.6$
RAFM	10

3. Activation evaluation for W/Cu/CuCrZr and W/V/ARAA divertors

3.1 Neutron flux and energy spectrum

Fig. 2 and 3 show the results of neutron energy spectrum with W/Cu/CuCrZr and W/V/ARAA divertor models, respectively. Table 2 presents the neutron flux calculated based on an NWL of 1.7058 MW/m². The results indicate that there were no significant differences in the neutron energy spectra between the two models in the W armor, H₂O coolant, and ARAA cassette body regions. In contrast, differences were observed in the low-energy region (below 0.1 MeV) within the interlayer and HS regions, where material compositions differ. Nevertheless, it was confirmed that the total neutron flux did not vary significantly between the two divertor models.

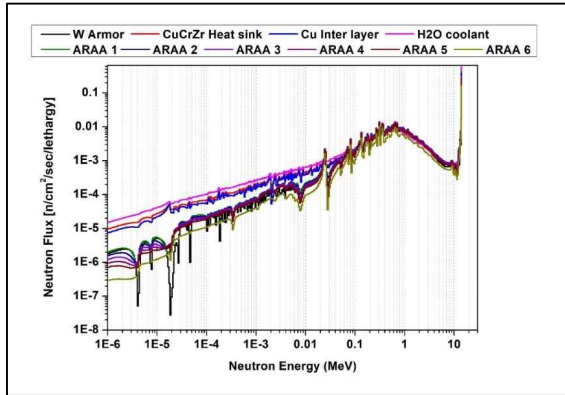


Fig. 2. Neutron energy spectrum in the W/Cu/CuCrZr divertor

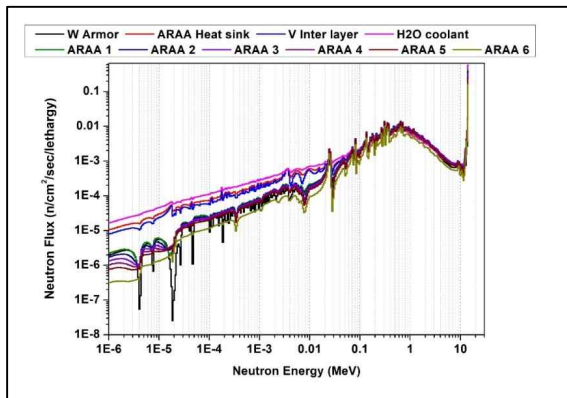


Fig. 3. Neutron energy spectrum in the W/V/ARAA divertor

Table 2. Neutron flux in W/Cu/CuCrZr and W/V/ARAA divertors

Neutron Flux (n/cm ² /s)			
W/Cu/CuCrZr divertor		W/V/ARAA divertor	
W	2.38E+14	W	2.37E+14
Cu	2.43E+14	V	2.43E+14
CuCrZr	2.43E+14	ARAA (Heatsink)	2.44E+14
H ₂ O	2.42E+14	H ₂ O	2.43E+14
ARAA	2.58E+14	ARAA	2.57E+14

3.2 Activation analysis

Fig. 4 presents the activation evaluation results for the two divertor models as a function of cooling time. Regardless of the model configuration, the W armor and ARAA (cassette body) exhibited similar decay behaviors; both showed high initial activity that decreased rapidly after 0.1 and 1 year of cooling, respectively. In the interlayer region, Cu demonstrated a significantly slower reduction rate compared to V. Specifically, the activity of Cu remained at approximately 10⁸ Bq/g even after 100 years of cooling, whereas that of V dropped to around 10⁴ Bq/g. Similarly, in the HS region, the activity of ARAA decreased sharply after 20 years, while CuCrZr

maintained a high level of activation.

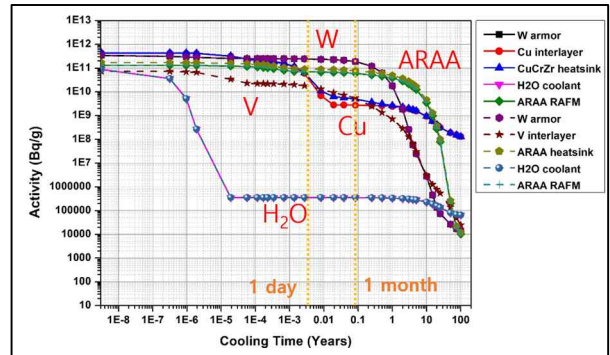


Fig. 4. Activity with cooling time in W/Cu/CuCrZr (solid line) and W/V/ARAA (dotted line) divertors.

The contact dose rate evaluation results, as shown in Fig. 5, indicate that the dose rates for V in the interlayer region decrease rapidly after 3 days of cooling, reaching the low levels after 100 years. In contrast, Cu maintains a high dose rate of 10⁻³ Sv/hr even after 10 years of cooling. Similarly, in the HS region, the dose rate of ARAA exhibits a much faster decline compared to that of CuCrZr after 1 year of cooling.

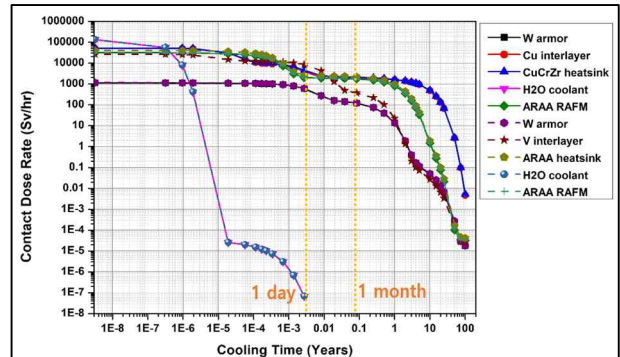


Fig. 5. Contact dose rate with cooling time in W/Cu/CuCrZr (solid line) and W/V/ARAA (dotted line) divertors.

The decay heat evaluation results in Fig. 6 also show that the heat generation of Cu-based materials (Cu, CuCrZr) remained the highest among all materials until 100 years of cooling. The slow activity reduction and high contact dose rate and decay heat of Cu-based materials are due to the ⁶⁰Co(⁶³n, α⁶⁰Co) and ⁶³Ni(⁶³Cu(n, p)⁶³Ni) nuclides generated through neutron reactions.

In particular, from a radioactive waste classification perspective, while W and ARAA decay to levels qualifying as Low-Level Waste (LLW), Cu and CuCrZr face technical limitations. Even after 100 years of cooling, the concentrations of ⁶⁰Co and ⁶³Ni in these materials exceed the regulatory limits, resulting in their classification as Intermediate-Level Waste (ILW).

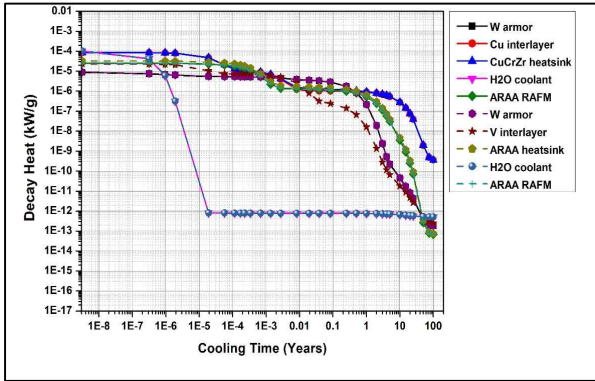


Fig. 6. Decay heat with cooling time in W/Cu/CuCrZr (solid line) and W/V/ARAA (dotted line) divertors

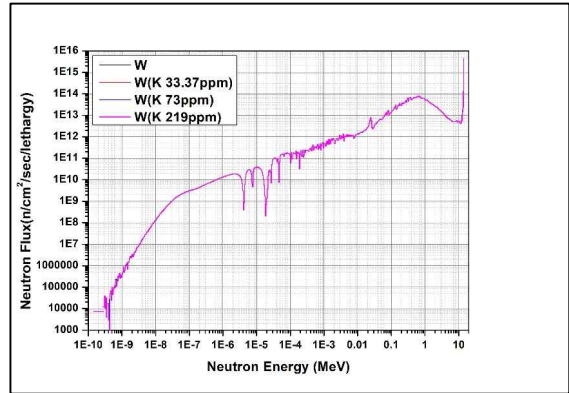


Fig. 7. Neutron flux with W in K-doped W/Cu/CuCrZr divertors

4. Activity analysis of K-doped W

The effect of K, added to increase the recrystallization temperature of the tungsten armor, was evaluated through an activation analysis. For this assessment, the K concentrations in the W armor were set to 73 ppm (pre-processing), 33.37 ppm (post-processing), and 219 ppm (three times the pre-processing level). These values were compared with a reference W containing approximately 10 ppm of K impurities.

As shown in Fig. 7, increasing the K content to 219 ppm did not result in significant changes to the neutron flux or energy spectrum within the divertor. This trend remained consistent for both the K-doped W/Cu/CuCrZr and K-doped W/V/ARAA models. Fig. 8-10. show the activity, contact dose rate, and decay heat as a function of K content. The analysis revealed that while K concentration had a similar impact on radioactivity and decay heat, it exhibited a different trend for the contact dose rate. Specifically, no significant variations were observed in the contact dose rate across different K concentrations. In contrast, differences in activity and decay heat began to emerge after 2–3 years of cooling and became more pronounced after 10 years, with both values increasing proportionally to the K content. The primary cause of these differences lies in the K transmutation reaction mechanism, $^{39}\text{K}(n,p)^{39}\text{Ar}$. The resulting ^{39}Ar has a very long half-life of 268 years, making it a key factor in the long-term increase in activity concentration and decay heat. Conversely, ^{39}Ar , a beta-decaying nuclide, contributes very little to the contact dose rate, which is dominated by gamma-ray emission.

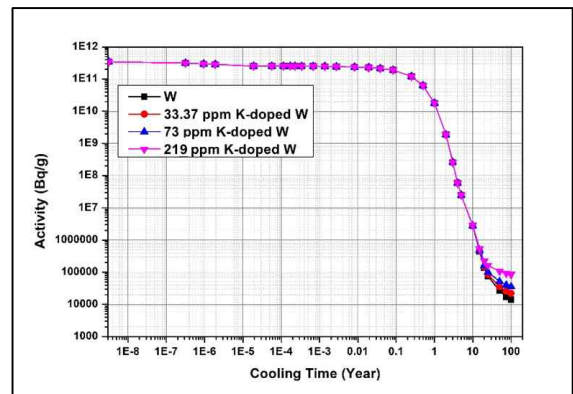


Fig. 8. Activity with cooling time of W in K-doped W/Cu/CuCrZr divertors

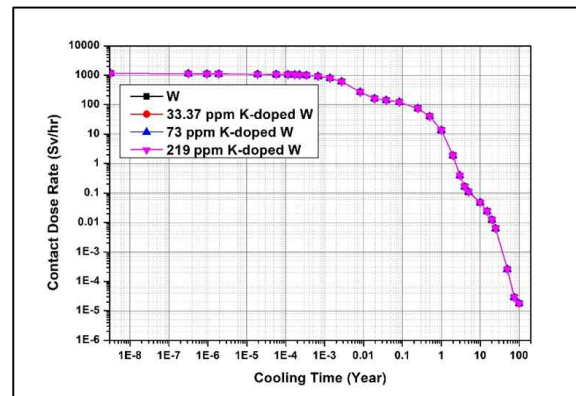


Fig. 9. Contact dose rate with cooling time of W in K-doped W/Cu/CuCrZr divertors

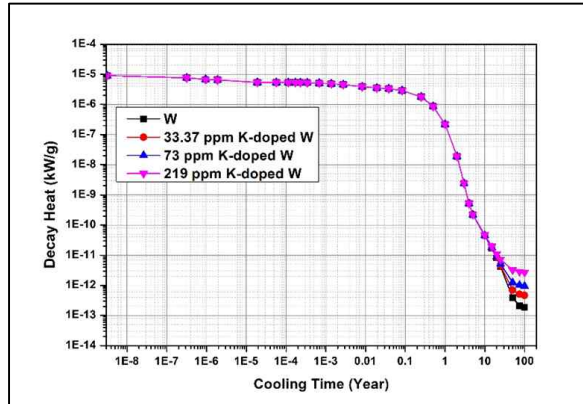


Fig. 10. Decay heat with cooling time of W in K-doped W/Cu/CuCrZr divertors

5. Conclusions

In this study, a comparative evaluation of the activation characteristics of W/Cu/CuCrZr and W/V/ARAA divertors was conducted. Furthermore, the activation effects of utilizing K-doped W to enhance the recrystallization temperature of the tungsten armor were precisely analyzed.

The material-wise comparison revealed that while all components exhibited high initial activity, their activity reduction rates differed significantly. Specifically, W, ARAA, V, and the H₂O coolant showed rapid declines in activity, contact dose rate, and decay heat after one year of cooling. In contrast, Cu and CuCrZr maintained high activity and contact dose rates even after 100 years. The slower decay rate of these Cu-based materials was confirmed to be attributed to the long-lived radionuclides ⁶⁰Co and ⁶³Ni generated through nuclear transmutation. Therefore, the use of Cu-based materials in DEMO grade divertors poses significant challenges.

Analysis of the effects of K-doped W revealed that increasing the K content in W to 219 ppm resulted in minimal changes in the neutron energy spectrum. While K addition increases activity and decay heat after 10 years of cooling by generating ³⁹Ar with a half-life of 268 years through the ³⁹K(n,p)³⁹Ar reaction, it demonstrated minimal impact on the contact dose rate due to the nature of beta decay nuclide. Consequently, there seem to be no major limitations in adopting K-doped W for divertor applications

Acknowledgement

This research was supported by the National Research Council of Science & Technology (NST) grant by the Korea Government (MSIT) (No. GTL25031-110).

REFERENCES

- [1] Polunovskiy E., 'C-model_R181031 model document', ITER IDM XETSWC.
- [2] Copper and copper alloys – compendium of composition and products; CEN/TS 13388:2004, p. 12.

[3] ITER Material Properties Handbook, IDM 222YLY.
[4] B. Pelowitz, M. James, A. Fallgren et al., Monte Carlo N-Particle® Transport Code System Version 6.1.1beta, Los Alamos National Laboratory LA-CP-14-00745, Rev.0 June 2014.

[5] FENDL 3.1 library Home: <https://www-nds.iaea.org/fendl/>

[6] M. Fleming, T. Stainer, and M. Gilbert, 'FISPACT-II User Manual', UKAEA-R (18)001 report, 2018.

[7] TENDL2017 library Home: https://tendl.web.psi.ch/tendl_2017/tendl2017.html